DOMES ON EUROPA: THE ROLE OF THERMALLY INDUCED COMPOSITIONAL DIAPIRISM. R. T. Pappalardo and A. C. Barr, University of Colorado, Boulder, CO 80309-0397 (robert.pappalardo@colorado.edu).

Overview: The surface of Europa is peppered by topographic domes, interpreted as sites of intrusion and extrusion. Diapirism is consistent with dome morphology, but thermal buoyancy alone cannot produce sufficient driving pressures to create the observed dome elevations. Instead, we suggest that diapirs may initiate by thermal convection that induces compositional segregation within Europa's ice shell. This double-diffusive convection scenario allows sufficient buoyancy for icy plumes to create the observed surface topography, if the ice shell has a very small effective elastic thickness (~0.1 to 0.5 km) and contains low-eutectic-point impurities at the percent level.

Thermal Buoyancy: Thermal diapirism has been proposed as a source of buoyancy for forming Europa’s domes [1,2]. Solid-state convection is capable of bringing warm material to shallow (several km) depths within Europa's ice shell [3]; however, stresses due to thermally driven convection are small. The maximum convective stress is

$$P_d \sim 0.1\, \rho_i\, g\, \alpha\, \Delta T\, D \qquad (1)$$

[4], where ρ_i is ice density, g is gravitational acceleration (1.3 m s^{-2} for Europa), α is the coefficient of thermal expansion, ΔT is the temperature difference across the ice shell, and D is the ice shell thickness.

For $\alpha = 10^{-4}$ K^{-1} and $\Delta T = 160$ K, the $P_d \sim 4 \times 10^4$ Pa within an ice shell of $D \approx 20$ km thickness. Numerical modeling of convection and associated thermal diapirism supports this analysis, predicting relief of only ~10 m above convective upwellings [5].

Diffusive cooling can cause diapirs to stall in the subsurface [2]. If warm diapirs reach the surface, thermal diffusion further robs buoyancy, and domes relax as they cool [6] if not supported by dynamic processes or compositional density variations [cf. 7].

Compositional Buoyancy and Double-Diffusive Convection: Differences in impurity levels serve as a potential source of compositional buoyancy to drive diapiric rise, and may be relevant to Europa dome formation (Fig. 1). Galileo NIMS results indicate non-ice materials on Europa, modeled as hydrated sulfate salts [8] or sulfuric acid hydrate [9], but the level of contaminants within the ice is highly uncertain.

A convecting icy shell is expected to have a nearly isothermal adiabatic temperature, T_{ad}, beneath a rigid stagnant lid. For a basally heated pure ice shell, T_{ad} can be as low as ~245 K [3], while for an internally (tidally) heated ice shell, T_{ad} is 250 to 260 K [6,10].

Both sulfate and chloride contaminants are plausible constituents of Europa's icy shell [11]. Hydrated sulfate salts have eutectic temperatures [12] ~270 K, securely above the predicted T_{ad} for Europa; therefore, these salts are expected to be stable against eutectic melting. However, the eutectic temperatures of hydrated chloride salts are in the range ~220 to 250 K, i.e. less than or comparable to the expected T_{ad}. Moreover, the ice-H_2SO_4 system has a eutectic of 211 K [11]. If hydrated chloride salts or sulfuric acid (herein collectively termed "low-eutectic" contaminants) exist within Europa's ice shell, they are expected to melt and produce brines in response to thermal convection. This should be the case throughout the warm base of the ice shell, and wherever a warm ice plume contacts colder contaminant-rich ice.

Melt is expected to drain through the ice at ~10 m yr^{-1} [13], significantly faster than the ~0.1 to 1 m yr^{-1} vertical velocity of convective ice plumes [3]. Therefore, the warm base of the ice shell and the convective plumes that rise from it are expected to be relatively clean of low-eutectic impurities (Fig. 1). In this model, low-eutectic contaminants are expected to become depleted in the ice shell over time unless replenished. It is plausible that Europa's ice shell is not in steady-state, but that instead its youthful surface age (~30 to 80 Myr [14]) reflects a latest incarnation of the ice shell, which began as relatively contaminant-rich and is more recently depleted in contaminants over time.

The warmer ice of a rising diapir will be cleaner and thus compositionally buoyant relative to its surroundings. Assuming isostasy above a column cleaned of low-eutectic contaminants through diapiric rise,

$$P_d = \phi(\rho_{le} - \rho_o)\, g\, D \qquad (2)$$

where ρ_{le} is the average density of the low-eutectic solids, ρ_o is the ambient density of the impure ice shell, and ϕ is the volume fraction of low-eutectic contaminants that melt and drain from diapiric plumes.

Choosing $\rho_o = 1000$ kg m^{-3} and $\rho_e = 1500$ kg m^{-3}, $\phi \sim 2\%$ can produce $P_d \sim 10^5$ Pa for a range of reasonable ice shell thicknesses, sufficient to upwarp domes to observed (~100 m) heights for intrusions beneath a brittle ice cover of T_e ~0.1 to 0.5 km for Young's modulus $E \sim 10^9$ to 10^{10} Pa The minor amounts of low-eutectic contaminants required are consistent with geochemical models of Europa's evolution [11].

The thermo-compositional buoyancy scenario envisioned here is essentially one of double-diffusive convection (DDC), in which both thermal and compositional gradients exist to trigger fluid motions [e.g., 15], as governed by the standard thermal Rayleigh number

$$\mathrm{Ra} = \rho g \alpha \Delta T D^3 / \kappa \eta \qquad (3)$$

(where α is the coefficient of thermal expansion, ΔT is the temperature drop across the convecting layer, κ is the thermal diffusivity, and η is viscosity), as well as a compositional Rayleigh number

$$\mathrm{Ra_c} = \rho g \beta \Delta C D^3 / \kappa \eta \qquad (4)$$

(where β is a compositional counterpart to α, and ΔC is the vertical composition gradient across the convecting layer).

The system operates in the "finger" regime, where compositionally buoyant material can rise in narrow upwellings of scale much smaller than the thickness of the convecting system, if

$$\mathrm{Ra}_c - \mathrm{Ra} > \frac{27}{4}\,\square^4 \qquad (5)$$

[16], whereas the system is in the diffusive regime typical of thermal convection for lesser values of (Ra_c – Ra). This relationship can also be expressed in terms of temperature and concentration gradients as

$$\frac{\square_o g D^4}{\square}\left[\frac{\square\square C}{\square_c D} - \frac{\square\square T}{\square D}\right] > 657 \qquad (6)$$

where $\square_c$ is the compositional diffusivity. For concentrations expressed as volume fraction f, then $\square C = \square\square$, and $\square = (\square_e - \square_o) / \square_o$.

For Europa, the value of $\square_c$ can be envisioned as governed by the melt composition, the velocity of melt drainge v_m, and a characteristic length scale for melt drainge L, as

$$\square_c \sim \square_{le}\square v_m L \qquad (7)$$

where $\square_e$ is the volume fraction of low-eutectic contaminants in the melt. The length scale L is unknown but may be in the range ~1 to 10% of the scale of a diapir, or ~70 to 700 m. Choosing plausible values of $\square \sim 0.02$, $\square_e \sim 0.1$, and $v_m \sim 10$ m yr^{-1}, then $\square_c \sim 4 \times 10^{-7}$ to 4×10^{-8} m^2 s^{-1}. Assuming a mean ice viscosity of ~10^{18} Pa s, $\square \sim 10^4$ m^2 s^{-1}, $\square T \approx 160$ K, and $D \sim 20$ km, then (Ra_c – Ra) ~ 250 to 2500. This suggests that Europa's ice shell may be transitional between the diffusive and finger regimes, but uncertainty in L and $\square_c$ implies that this coarse estimate must be refined.

Summary and Implications: The required buoyancy to account for Europa's domes is difficult to achieve through thermal convection alone but can be produced by percentage level compositional differences between ice diapirs and their surroundings, if low-eutectic contaminants melt and drain from warm ice plumes, and if the effective thickness of the brittle lithosphere is very small (~0.1 to 0.5 km). This implies that convection in Europa's ice shell is best modeled as double-diffusive convection, in which thermal and compositional gradients are both important. Convection in the compositionally dominated finger regime can result in upwelling diapirs that are significantly smaller in scale than the vertical scale of the convecting medium, so attempts to relate lenticula size to Europa's ice shell thickness may not be fruitful.

Thermally induced compositional buoyancy offers a comprehensive and geophysically plausible means for forming Europa's domes. An analogous model has been applied to Europa's bands by [7], and is potentially applicable to the satellite's larger chaos regions as well. The model implies significant compositional inhomogeneity on a local scale within the ice shell, which might be directly detectable by future missions using ground penetrating radar. This process would allow deep interior material to breach the Europa's cold brittle lithosphere, with potential implications for transport of oceanic and astrobiologically relevant materials to the surface.

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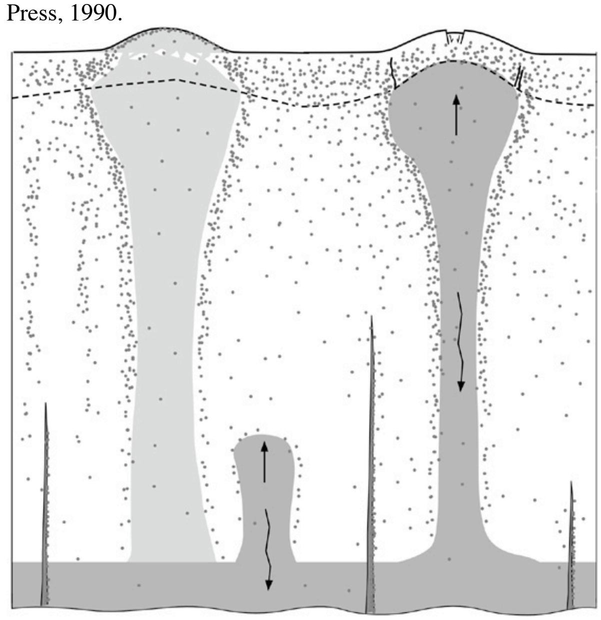

Fig. 1: Schematic illustration of the thermally induced compositional diapirism model. As warm ice (dark gray) near the base of Europa's ice shell begins to rise diapirically, it melts overlying low-eutectic contaminants (stipples) and the brines drain downward (squiggly arrows), allowing compositional buoyancy to aid diapir rise toward the surface. Buoyant diapiric material can breach the cold brittle lithosphere and extrude to form a dome (lefft); contaminants remaining in the diapiric ice are then concentrated by exogenic processes. Alternatively, diapirs can intrude and upwarp the brittle lithosphere to form intrusive domes (right). Low-eutectic contaminant concentration is least in the warmest ice and locally concentrated in halos surrounding diapirs from which they have been expelled. Dome topography and subsurface compositional gradients persist whether the underlying ice column is warm or has cooled (left, lighter gray), until subsequent diapirism redistributes the constituents. Diking might replenish some contaminants from the ocean below, but the ice shell is expected to be overall depleted in low-eutectic contaminants over time.